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Cryogenic Liquid-Jet Breakup in Two-Fluid Atomizers

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CRYOGENIC LIQUID-JET BREAKUP IN TWO-FLUID ATOMIZERS

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ABSTRACT

A two-fluid atomizer was used to study the breakup of liquid-nitrogen jets in nitrogen, argon and helium atomizing-gas flows. A scattered-light scanner particle sizing instrument previously developed at NASA Lewis Research Center was further developed and used to determine characteristic drop diameters for the cryogenic sprays. In the breakup regime of aerodynamic-stripping, i.e., sonic-velocity conditions, the following correlation of the reciprocal Sauter mean diameter, D_{32}^{-1}, with the atomizing-gas flowrate, W_g, was obtained: $D_{32}^{-1} = k_c W_g^{1.33}$, where k_c is a proportionality constant evaluated for each atomizing gas. Values of k_c = 120, 220 and 1100 were obtained for argon, nitrogen and helium gasflows respectively. The reciprocal Sauter mean diameter D_{32}^{-1} and gas flowrate, W_g, have the units of cm^{-1} and g/sec, respectively.

In the regime of capillary-wave breakup, or subsonic conditions, it was found that; $D_{32}^{-1} = k_g W_g^{0.75}$, where k = 270, 390 and 880 for argon, nitrogen and helium gasflows, respectively.

INTRODUCTION

The drop size of disintegrating liquid jets in low velocity airflow is controlled primarily by a capillary-wave mechanism and characteristic particle size is generally relatively large. However when a liquid jet is injected into high velocity or sonic flows, an aerodynamic stripping mechanism occurs in which the jet is disintegrated into a large number of small liquid particles, thereby producing a large liquid surface area. In this case, disintegration occurs before waves have time to form on the liquid-jet surface. The emphasis of the present study was on the mechanism of aerodynamic-stripping, in which two-fluid nozzles were used to impact liquid-nitrogen jets with argon, nitrogen and helium atomizing-gas flows.

Cryogenic liquid-jets with atomizing-gas flows injected into rocket combustors are quickly disintegrated into small-droplet sprays. In order to calculate vaporization or burning rates, it is necessary to characterize the spray in terms of drop size distribution and mean drop size such as the Sauter mean diameter. Once characteristic drop sizes are known, mathematical expressions can be derived to adequately describe a two-fluid atomization process in which various liquid propellants and atomizing-gas combinations are used to enhance spray combustion and yield high combustor performance over a wide range of operating conditions.

Knowledge of the characteristic size of drops in sprays are also needed in experimental studies of fuel-spray combustion in diesel and other internal combustion engines and gas turbine combustors. In addition, knowledge of water sprays is needed to study the formation of ice on airfoils in icing wind tunnel experiments. In the task of characterizing sprays, detailed knowledge of the mechanics of liquid-jet disintegration is especially needed at the point of initial spray formation close to the atomizer orifice. This is especially true in the study of highly volatile cryogenic liquids. From this knowledge, accurate initial conditions can be established for modeling a fuel spray combustion process or modelling the process of ice formation on airfoils.

Numerous investigators have obtained experimental drop size data and correlated it with relative velocity, i.e., gas velocity relative to liquid velocity and also with liquid properties, as given in Refs. 1 to 7. Some of the correlations do not agree very well with atomization theory; which is generally attributed to the fact that measurement techniques and drop sizing instruments have yet to be developed and standardized to the extent that good agreement might be expected. The fluid property having the greatest effect on the drop size of sprays produced with two-fluid nozzles is the gas velocity. Although numerous investigators have studied this phenomena, the effect of gas mass flux on the drop size of cryogenic sprays has not been established in the spray literature. Therefore, the main objective of the present study was to determine the effect of atomizing-gas mass flux on liquid-nitrogen spray characteristics.

Prior to the present study, an investigation of water sprays was made with two-fluid nozzles and good agreement of experimental results with atomization theory was obtained, as discussed in Ref. 1. It was found that the Sauter mean diameter, D_{32}, could be correlated with nitrogen gas flowrate, W_n, raised to the -1.33 power, which agrees well with theoretical expressions for liquid jet breakup in high velocity gasflow. As a continuation of this study, the present investigation was initiated to extend experimental conditions to include cryogenic liquid-jet breakup in helium, argon, and nitrogen gas flows.

Two-phase flow in which transfer of momentum from low velocity and sonic gasflows to the surface of liquid-nitrogen jets was experimentally investigated by using three different atomizing gases to produce clouds of liquid-nitrogen droplets. Tests were conducted in the capillary-wave and aerodynamic-stripping regimes of disintegrating liquid jets. A scattered-light scanning instrument developed at NASA Lewis Research Center was used to measure characteristic drop diameters of the cryogenic-liquid sprays. By correcting for gas turbulence and thermal gradient effects on measurements, reproducible data was obtained with the scattered-light scanner. To avoid the loss of small liquid-nitrogen droplets due to their high vaporization rate, measurements were taken close to the nozzle orifice. The entire spray cross section was sampled with a 4.4 by 1.9 cm rectangular laser beam, at an axial distance of 1.3 cm downstream of the atomizer.

APPARATUS AND PROCEDURE

A two-fluid nozzle was mounted in the test section as shown in Fig. 1, which also shows the optical path of the scattered-light scanner. Air supplied at ambient temperature, 293 K, passed through the 15.24 cm inside diameter test section and exhausted to the atmosphere. The test section was 1 m in length and a 5.08 cm diameter orifice was used to measure the air flowrate in the test section. A flow of dry air at a velocity of 5 m/sec was maintained in the test section to aid in transporting small droplets through the laser beam. This prevented ambient humid air from contacting the spray and thereby avoided the formation of ice particles in the laser beam.

A detailed diagram of the two-fluid nozzle is shown in Fig. 2. It was mounted in the center of the test section and operated over pressure ranges of 0.2 to 1.0 MPa for both liquid nitrogen and the atomizing gases. Liquid nitrogen sprays were injected downstream into the airflow just upstream of the duct exit. The spray was sampled at a distance of 1.3 cm downstream of the atomizer orifice with a 4.4 by 1.9 cm rectangular laser beam produced by the 0.01 cm diam aperture shown in Fig. 1.

Liquid nitrogen, LN_2, at a temperature of 77 K measured with an I.C. thermocouple, was axially injected into the airstream at a flowrate of 27.5 g/sec, as indicated by a turbine flow meter. The atomizing gas was then turned on to break up the LN_2 jet and weight flow rate was measured with a 0.51 cm diameter sharp-edge orifice. After the air, atomizing-gas and LN_2 flow rates were set, characteristic drop diameters were determined from measurements made with the scattered-light scanner.

The optical system of the scattered-light scanner is shown in Fig. 1. The instrument measures scattered-light as a function of scattering angle by repeatedly sweeping a variable-length slit in the focal plane of the collecting lens. The data obtained is scattered-light energy as a function of the scattering angle relative to the laser-beam axis. This method of particle size measurement is similar to that given in Ref. 8 and it is described in detail in Ref. 9. Calibration was accomplished with five sets of monosized polystyrene spheres having diameters of 8, 12, 25, 50 and 100 μm. Since the sprays were sampled very close to the atomizer orifice, they contained a relatively high number of very small drops. As a

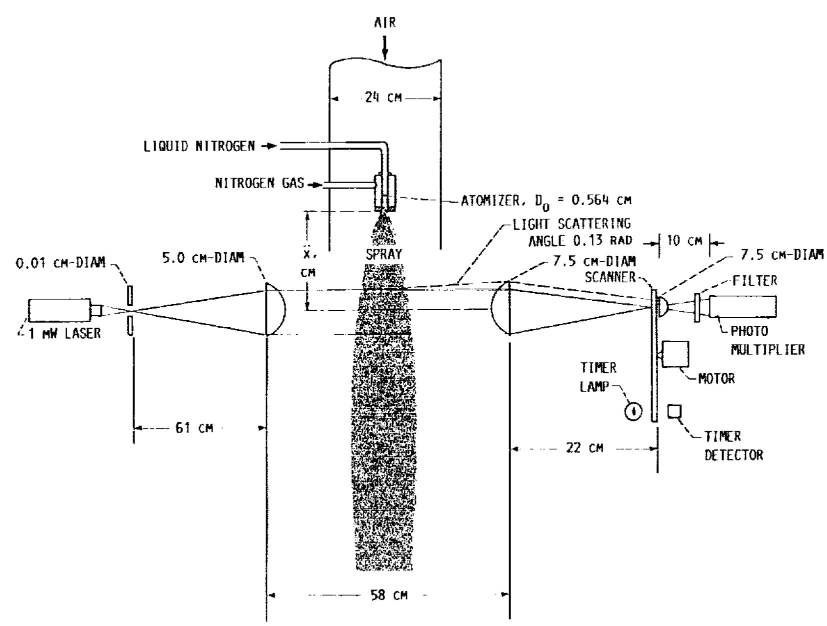

FIGURE 1. - ATMOSPHERIC PRESSURE TEST SECTION AND OPTICAL PATH OF SCATTERED-LIGHT SCANNER.

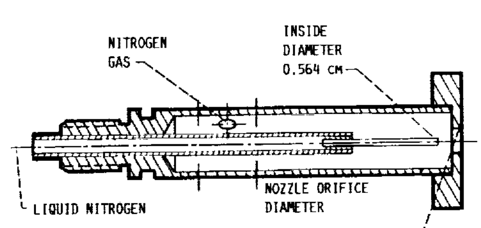

FIGURE 2. - DIAGRAM OF PNEUMATIC TWO-FLUID ATOMIZER.

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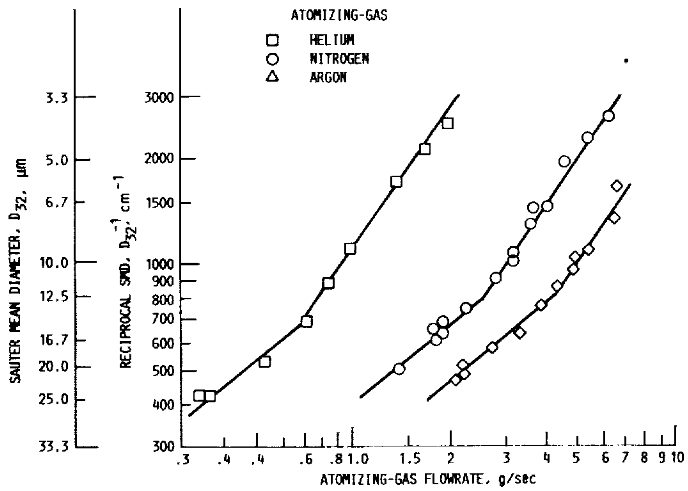

FIGURE 3. - CORRELATION OF SAUTER MEAN DIAMETER WITH ATOMIZING-GAS FLOWRATE.

result, the light-scattering measurements required correction for multiple scattering as described in Refs. 9 and 10 for the case of high concentrations of droplets. Drop size measurements were also corrected as described in Ref. 9 to include Mie scattering theory when very small characteristic droplet diameters, i.e., <10 µm, were measured.

Atomizing-gas temperatures were approximately 293 K and surface temperatures of the liquid-nitrogen jets were always near the boiling point of liquid-nitrogen, i.e., approximately 77 K. This created large temperature gradients that deflected the laser beam and caused beam steering to occur. However, by carefully adjusting the laser beam away from the slit in the scattered-light scanner optical system, the effect of beam steering on measurements was negligible.

EXPERIMENTAL RESULTS

As shown in Fig. 1, the entire spray cross section was sampled at an axial distance of $\bar{x} = 1.3$ cm downstream of the two-fluid atomizer orifice. Values of the Sauter mean diameter, D_{32}, and reciprocal SMD, D_{32}^{-1}, are plotted against atomizing-gas flowrate as shown in Fig. 3. Tests were conducted over a relatively wide range of atomizing-gas flowrates that included both subsonic and sonic gas-velocity conditions.

At relatively low or subsonic atomizing-gas flow conditions, breakup of the LN_2 jets occurred primarily in the capillary-wave regime of atomization and the following general correlation of D_{32}^{-1} with gas flowrate, W_g, was obtained:

$$D_{32}^{-1} = k_g W_g^{0.75}$$

where the reciprocal SMD and gas flowrate are expressed as cm^{-1} and g/sec, respectively. The correlating constant $k_g = 270$, 390 and 880 when argon, nitrogen and helium, respectively, were used to atomize the LN_2 jets. The exponent 0.75 for W_g is approximately 10 percent higher than the 2/3 exponent given for gas velocity in the theoretical expression reported in Ref. 11.

In regime of aerodynamic-stripping or sonic-velocity atomizing-gas flow conditions, the following expression was obtained:

$$D_{32}^{-1} = k_c W_g^{1.33}$$

where the correlating constant $k_c = 110$, 220 and 1100 when argon, nitrogen and helium, respectively were used as atomizing gases. The exponent 1.33 for W_g is the same at the 4/3 exponent given for gas velocity in Ref. 11. Thus, good agreement with atomization theory was obtained in the regime of aerodynamic stripping conditions.

Transition from the regime of capillary-wave breakup to that of aerodynamic-stripping occurred at values of $D_{32}^{-1} = 700$ cm^{-1} or $D_{32} = 15$ µm,

Table 1 Proportionality constant, k, and gas flowrate exponent, x, for correlating expression:

$$D_{32}^{-1} = k\, W_g^x$$

Breakup regime	Argon	Nitrogen	Helium
Capillary-wave:			
k_g, constant	120	220	1100
x, exponent	0.75	0.75	0.75
Aerodynamic-stripping:			
k_c, constant	270	390	880
x, exponent	1.33	1.33	1.33

approximately, for the atomizing gases used in the present study. Values of k_c and k_g are given in Table 1.

CONCLUDING REMARKS

The fluid mechanics of liquid-nitrogen jet breakup is much more difficult to study than the atomization of fuel or water jets. This is primarily due to the fact that surface temperatures of the liquid-nitrogen jets used in the present study were always near the boiling point of liquid nitrogen, i.e., approximately 77 K. Since the atomizing gases were at room temperature, approximately 293 K, this created large temperature gradients that deflected the laser beam and caused beam steering to occur as characteristic drop diameter was measured with the scattered-light scanner. This problem was minimized in the present investigation by moving the laser beam away from the slit in the scattered-light scanner optical system.

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